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Research Article

# On the Ontology of Superheavy Elements

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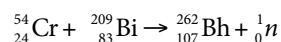
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**Abstract.** The study of so-called superheavy elements with atomic numbers  $Z > 102$  has for several decades been a major research field in nuclear physics and chemistry. Presently all elements up to and including  $Z = 118$  have been discovered and assigned official names by IUPAC. To speak of “discovery” is however unfortunate since the elements are in reality produced, manufactured or created in the laboratory. They are not found in nature. Moreover, it is not obvious that they exist in the normal sense of the term or that they can be called elements at all. Apart from sketching the history of transuranic and superheavy elements, the paper focuses on some of the philosophical issues which are relevant to the synthesis of very heavy elements at the end of the periodic table. In addition, the relationship between superheavy elements and exotic atoms (such as anti-atoms and muonic atoms) are briefly considered.

**Keywords.** Superheavy elements, nuclear chemistry, transuranic elements, discovery, periodic table.

## 1. INTRODUCTION

For more than half a century the synthesis and study of very heavy chemical elements have attracted much attention not only scientifically but also in the public sphere. What are known as superheavy elements, commonly abbreviated SHEs (SHE in the singular), are investigated in a few large and very expensive research facilities currently located in Russia, the United States, Germany, and Japan. Whereas the transuranic elements up to  $Z = 100$  were produced by means of neutron capture or irradiation with alpha particles, since the late 1960s the basic method of synthesis has been heavy-ion collisions where a target of a heavy element is bombarded with accelerated ions of a lighter element. For example, in 1981 a few atoms of element 107 (bohrium) were produced in the nuclear reaction



In so far that SHE research is concerned with the formation of new atomic nuclei and relies crucially on advanced accelerator and detection technology, it is a branch of nuclear physics rather than chemistry. On the other hand, in the identification of new nuclides methods of nuclear chemistry are indispensable.

More importantly, SHEs are about elements and there is a long historical tradition that everything concerning new elements belong to the domain of chemistry. The responsibility of recognizing new elements still belongs to IUPAC (the International Union of Pure and Applied Chemistry) and not to the physicists' sister organization IUPAP (the International Union of Pure and Applied Physics). The distinction between physics and chemistry in modern SHE research is in some way artificial as workers in the field rarely consider themselves as either physicists or chemists. Nonetheless, the relationship between the two sister sciences in this research area has often been characterized by controversy rather than harmony.<sup>1</sup>

While the scientific literature on the synthesis and properties of SHEs is dauntingly large, there is no comprehensive history of SHE research. What has been written is limited to reviews from the perspective of the scientists participating in the development.<sup>2</sup> Next to nothing has been written on the subject from a proper historical perspective and even less from a philosophical perspective. And yet, as Eric Scerri points out, the synthesis of SHEs "has raised some new philosophical questions regarding the status of the periodic law."<sup>3</sup> The subject is indeed of considerable interest from the point of view of history, philosophy and sociology of science.<sup>4</sup>

In this paper I focus on the crucial notion of what constitutes a chemical element. Can one reasonably

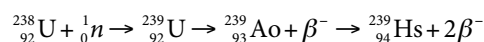
claim that superheavy elements exist in the same sense that the element oxygen exists? After all, they are created in the laboratory and not discovered in nature such as has been the case with most elements. Apart from this ontological question, SHE research also involves the epistemic question of how knowledge of a new SHE is obtained and what the criteria for accepting discovery claims are. And, what is equally important, *who* are responsible for the criteria and for evaluating discovery claims? The latter questions are relevant to the paper, but not what it is primarily about. They deserve a fuller treatment.

The synthesis and scientific study of SHEs, not to mention the historical development of the field, may not be well known to the majority of chemists and historians of chemistry. For this reason I start with two introductory sections offering a brief historical account of how the early attempts in the 1930s to produce transuranic elements in the post-World War II era grew into the modern research area which may be best characterized as a hybrid between high energy physics and nuclear chemistry.

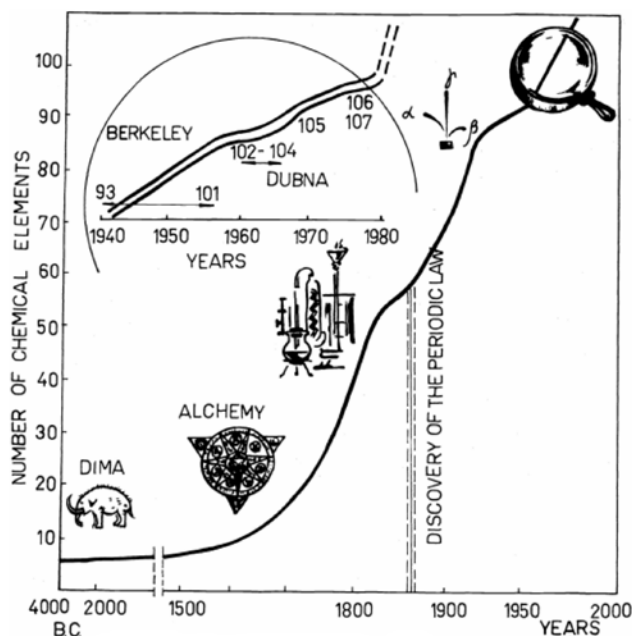
## 2. ARTIFICIAL CHEMICAL ELEMENTS

The periodic table consists presently of 118 elements, starting with hydrogen of atomic number  $Z = 1$  and ending with oganesson of  $Z = 118$ . About a quarter of the elements does not exist in nature or only exist in miniscule amounts. Twenty-six of the elements are transuranic, meaning that they have atomic numbers larger than the  $Z = 92$  for uranium, the heaviest of the naturally occurring elements. The name "transuranic" (German "Transurane") may first have been used by the German physicist and engineer Richard Swinne in a paper of 1926 dealing with the periodic system.<sup>5</sup> On the basis of Bohr's atomic theory Swinne proposed detailed electron configurations for elements with  $92 < Z < 108$ .

Although speculations concerning transuranic elements can be found as early as the late nineteenth century,<sup>6</sup> it was only with the development of nuclear physics in the 1930s that laboratory synthesis of the elements became a realistic possibility. Famously, Enrico Fermi and his research group in Rome thought for a short while to have obtained the elements 93 and 94 by bombarding uranium with slow neutrons:



The supposed but premature discovery of two new elements – provisionally called ausenium (Ao) and hesperium (Hs) – was part of the reason for awarding Fermi



**Figure 1.** A version of the history of element discoveries according to two leading Dubna scientists. Source: G. N. Flerov, G. Ter-Akopian, *Pure Appl. Chem.* **1981**, 53, 909, on p. 910. © IUPAC.

the Nobel Prize in physics in 1938.<sup>7</sup> It soon turned out that the announcement was a mistake. Only in 1940, when investigating fission fragments from neutron-irradiated uranium, did Edwin McMillan and Philip Abelson at the Berkeley Radiation Laboratory succeed in detecting element 93, soon to be named neptunium. The more important discovery of element 94 (plutonium) made by Glenn Seaborg, Arthur Wahl and Joseph Kennedy followed a year later. Due to the war it was only announced in public in a paper of 1946.

However, the first artificial element ever produced in the laboratory was sub-uranic and a result of Fermi's group in Rome. In 1937 Emilio Segré and his collaborator Carlo Perrier analyzed plates of molybdenum irradiated with deuterons and neutrons from the Berkeley cyclotron. They were able to identify two isotopes of element 43, for which they proposed the name "technetium" ten years later. There had earlier been several unconfirmed claims of having detected the element in natural sources, as reflected in names such as "masurium" and "illinium," but Segré and Perrier soon became recognized as discoverers.<sup>8</sup> Segré is also recognized as the co-discoverer, together with Dale Corson and Kenneth MacKenzie, of element 85 which was produced in Berkeley in 1940 by bombarding Bi-209 with alpha particles. In 1947 they suggested the name astatine for it. Tiny amounts of astatine exist in nature, and also in this case there were previous claims of having identified the very rare element.<sup>9</sup>

The early history of transuranic elements was completely dominated by a group of Californian chemists and physicists led by Seaborg and Albert Ghiorso. Elements 95 and 96 were first identified in 1944 at the Metallurgical Laboratory in Chicago and named americium (Am) and curium (Cm), respectively.<sup>10</sup> After the war followed the discovery of  $Z = 97$  (berkelium, Bk) and  $Z = 98$  (californium, Cf) which were announced in 1950. In 1951, at a time when six transuranic elements had been added to the periodic system, Seaborg and McMillan were awarded the Nobel Prize in chemistry "for their discoveries in the chemistry of the transuranium elements." Elements 99 and 100, named einsteinium (Es) and fermium (Fm), were first identified in late 1952, not in a planned experiment but in the fallout from a test of the American hydrogen bomb (the discovery team led by Ghiorso only published its findings in 1955, a delay caused by orders from the U.S. military). Also in 1955, the discovery of element 101 (mendelevium, Md) was announced by the Berkeley group using its cyclotron to irradiate a tiny sample of the einsteinium isotope Es-253 with alpha particles.

The Californian dominance in the synthesis of new transuranic elements was first challenged in connec-

tion with element 102. An isotope of this element was claimed discovered by experimenters in Stockholm in 1957 and some years later also by the Russian physicist Georgii Flerov and his group at the new Joint Institute for Nuclear Research (JINR) in Dubna outside Moscow. Founded in 1956, the Dubna institute soon became a most important centre for nuclear physics and chemistry.<sup>11</sup> Much of the later research in the synthesis of heavy transuranic elements was marked by an intense rivalry between the two research centres, one American (LBNL, Lawrence Berkeley National Laboratory) and the other Russian (JINR).

Although transuranic elements are artificial there is a faint possibility that some of their isotopes have a long life-time and are not exclusively the products of nuclear laboratories. Since about 1970 there have been numerous searches for heavy transuranic elements in nature, but so far not a single atom has been found. The exception is neptunium and plutonium which, strictly speaking, do occur naturally. However, the trace amounts found of these two elements are not of primordial origin but owe their existence to nuclear reactions in uranium such as neutron capture followed by beta decay. The two elements exist in nature in extremely low concentrations only, such as illustrated by the amount of plutonium in the uranium mineral pitchblende (largely  $\text{UO}_2$ ), which is about one part to  $10^{11}$ .

Several of the transuranic elements have been made in visible quantities and a few of them, such as long-lived isotopes of curium and americium, have even found applications in science and industry (many household smoke detectors contain the americium isotope Am-241). Plutonium is unique by being the only synthetic element produced in very large quantities, primarily a result of its use in nuclear weapons. It is estimated that today the world stockpile of the element is about 500 tons.<sup>12</sup> The long half-life of plutonium ( $2.4 \times 10^4$  years for Pu-239) means that the element is not just an ephemeral visitor on Earth but will remain with us for thousands of years to come. The heaviest isotope detected in nature is Pu-244 with a half-life of 81 million years.

### 3. A BRIEF HISTORY OF SUPERHEAVY ELEMENTS

The term "superheavy element" for the heaviest of the transuranic elements has no precise meaning but often refers to the transactinide elements with  $Z$  ranging from 103 to 120. The name owes its origin to the American physicist John Wheeler, who in the 1950s examined theoretically the limits of nuclear stability. However, it can be found even earlier, perhaps first in a 1938 review

paper on possible transuranic elements.<sup>13</sup> On the basis of the liquid drop model of nuclear structure Wheeler suggested that atomic nuclei twice as heavy as the known nuclei might be ascribed “experimental testable reality.”<sup>14</sup> With this phrase he implied that the nuclei should have a lifetime greater than  $10^{-4}$  second. The first scientific paper with “superheavy elements” in the title appeared in 1966 and fifty years later the cumulative number of such papers had grown to approximately 2,000.

Much of the impetus for SHE research derives from theories of nuclear structure and in particular from predictions based on the shell or independent-particle model developed in the late 1940s independently by Maria Goeppert Mayer in the United States and Hans Jensen and collaborators in Germany.<sup>15</sup> According to Mayer, nuclei with 2, 8, 20, 50, 82, and 126 protons or neutrons were particularly stable. These were “magical numbers” representing closed shells in the nucleus, an idea which mineralogists had anticipated much earlier. The first anticipation of magical numbers dates from 1921 and was due to the Swiss mineralogist Paul Niggli.<sup>16</sup>

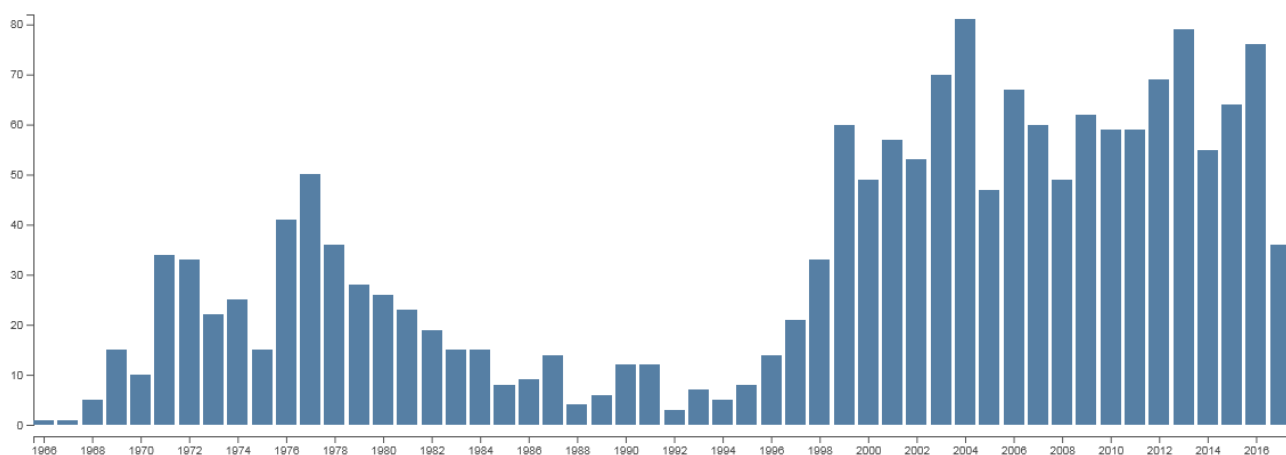
The theoretical possibility of a relatively stable element of  $Z = 126$  seemed remote from laboratory physics, but in the late 1960s more sophisticated nuclear models indicated that  $Z = 114$  rather than  $Z = 126$  was a magic number. The region around  $(Z, N) = (114, 184)$  – a “doubly magical” nucleus – was expected to represent nuclei with a relatively long half-life and therefore accessible to experimental study. The region became known as an “island of stability,” a term that may first have appeared in the physics literature in 1966.<sup>17</sup> The hope of the experimenters was to reach the fabled island, if it existed, either by manufacturing the nuclides or by finding them in nature. As a leading SHE physicist recalled, the predictions from nuclear theory “immediately stirred up a

gold-rush period of hunting for superheavy elements in natural samples.”<sup>18</sup>

Indeed, from about 1970 many researchers began looking for evidence of SHEs in cosmic rays, meteorites, terrestrial ores, or even samples of lunar matter.<sup>19</sup> The favoured method was to look for tracks due to spontaneous fission, a process which is exceedingly rare in nature but is the dominant decay mode for SHEs (the probability of spontaneous fission is roughly proportional to the parameter  $Z^2/A$ ). The first searches for natural SHEs were reported in 1969 by research groups from Berkeley and Dubna, and a decade later the search had grown into a minor industry. The search is still going on, but without any convincing evidence of naturally occurring SHEs.<sup>20</sup> Interesting as this chapter in SHE history is, in the present context there is no need to cover it.

One of the problems of reaching the island of stability is that by and large the half-lives of the longest-living nuclides decreases with the atomic number. While the half-life for Sg-269 ( $Z = 106$ ) is 3 minutes, it is 14 seconds for Ds-281 ( $Z = 110$ ), 2 seconds for Fl-289 ( $Z = 114$ ), and 0.7 milliseconds for Og-294 ( $Z = 118$ ). Another problem is the very low production rate, which typically is of the order of a few atoms per day and in some cases even lower. In spite of these and other problems all SHEs until and including element 118 have now been discovered and are officially recognized as citizens of the periodic kingdom.

The elements with  $Z$  ranging from 103 to 109 were synthesized in the two decades from 1965 to 1985, in all cases by means of heavy-ion fusion reactions where a target of a heavy element is bombarded with medium-sized ions. The elements were produced in a competitive race between scientists from Dubna and Berkeley, and since the mid-1970s also involving a third party in the form of the GSI (Gesellschaft für Schwerionenforschung)

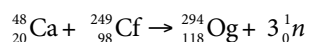


**Figure 2.** Number of scientific papers including the term “superheavy elements” in the title. Source: *Web of Science*.

in Darmstadt, Germany, established in 1969. In the present context there is no need to go into detail or to dwell on the many controversies between the research groups concerning priority and names.<sup>21</sup> Elements with atomic numbers 110, 111 and 112 were produced by the Darmstadt group in the years 1995 and 1996 and eventually named darmstadtium (Ds), roentgenium (Rg) and copernicium (Cn). The even heavier elements 114 and 116 (flerovium and livermorium) were first synthesized in Dubna by a Russian-American collaboration including scientists from LLNL, the Lawrence Livermore National Laboratory.

The most recent newcomers to the periodic table are the elements with atomic numbers 113, 115, 117 and 118, which all received official recognition in 2016. The first atoms of element 113, named nihonium (Nh) were produced in 2003-2005 by a team at the RIKEN Nishina Center for Accelerator-Based Science in Japan. Elements 115 and 117 were synthesized in experiments from 2010 by the Dubna-Livermore collaboration extended with scientists from the Oak Ridge National Laboratory in Tennessee. While element 115 was named moscovium (Mc), element 117 was assigned the name tennessine (Ts).

Element 118 was another product of the successful Dubna-Livermore collaboration led by the Dubna physicist Yuri Oganessian, a highly esteemed veteran in SHE research. In experiments of 2006 the team observed three decay chains arising from the fusion of Ca-48 and Cf-249, which was interpreted as due to the formation of the  $A = 294$  isotope of element 118, namely



The results obtained in 2006 were confirmed and improved in subsequent experiments, but it took until 2016 before the discovery was officially recognized and the new element was named oganesson (Og) in recognition of the leader of the discovery team.<sup>22</sup> Although no atoms of oganesson have ever been studied experimentally, calculations predict that its electron shell structure is

$$2, 8, 18, 32, 32, 18, 8,$$

and that it thus belongs to the group of noble gases. Remarkably, this is the very same structure that Bohr suggested back in 1922.<sup>23</sup>

#### 4. CRITERIA FOR DISCOVERIES

The history of discoveries and discovery claims of SHEs differs from the earlier history of most element

discoveries. The reason is that short-lived SHEs are produced artificially and in a small number of atoms only, sometimes one by one, and that the atoms can only be identified indirectly according to certain criteria of nuclear physics and chemistry. Moreover, new SHEs need to have the characteristics of ordinary elements in order to be placed in the periodic table alongside other elements. The organization responsible for accepting or dismissing discovery claims is IUPAC, which also authorizes the names and symbols of the elements. Bureaucratically speaking, an element is only an element when it has been officially approved by the IUPAC Council. The names of the transuranic elements were first considered at the 15th IUPAC conference in 1949, when the Commission on Nomenclature of Inorganic Chemistry (CNIC), a branch under IUPAC, officially adopted the proposed names for elements 93 to 96.<sup>24</sup>

During the first decades of the twentieth century there were two basic criteria for recognizing the discovery of a new element, namely the optical spectrum and the atomic weight of the claimed element. Since the mid-1920s the main criterion became the element's characteristic X-ray spectrum which directly reveals the atomic number.<sup>25</sup> The first element identified and recognized in this way was hafnium,  $Z = 72$ . However, for several of the superheavy elements none of these criteria are relevant since they have no definite atomic weight and also no spectrum based on electron transitions between different energy levels. Besides, X-ray spectroscopy requires amounts of matter much greater than the few atoms often produced in SHE reactions. The method could only be used indirectly, to determine the characteristic X-rays emitted by atoms of the daughter nuclide after the decay of the parent SHE nuclide.

The confusing number of discovery claims for new SHEs through the 1960s and 1970s inevitably caused reconsideration of the old question, what does it mean to have discovered a new element? Scientists engaged in SHE synthesis agreed that the atomic number was the defining parameter of an element, but they shared a concern over the confusion caused by missing operational criteria for SHE discoveries.

In 1971 Flerov and his Dubna colleague, the Czechoslovakian nuclear chemist Ivo Zvára, wrote a memorandum in which they pointed out that the concept of element belonged to chemistry and atomic physics and not to nuclear physics. "If the atomic number is established by chemical means or by techniques of atomic physics (Roentgen spectroscopy, etc.)," they stated, "then even without a nuclear-physics identification the work should be considered a discovery."<sup>26</sup> The following year

two nuclear chemists at the Lawrence Berkeley Laboratory similarly suggested that chemical methods to the identification of atomic numbers would be essential or at least complementary to methods of nuclear physics.<sup>27</sup>

On the proposal of the Dubna group, in 1974 IUPAC in collaboration with IUPAP appointed an ad hoc group of nine neutral experts, three of which were from the United States and three from the Soviet Union. According to the American members of the group, its purpose was “to consider the claims of priority of discovery of elements 104 and 105 and to urge the laboratories at Berkeley (USA) and Dubna (USSR) to exchange representatives regarding these experiments.”<sup>28</sup> However, the initiative was a failure as the committee never completed its work or issued a report. Indeed, it never met as a group.<sup>29</sup> According to Roger Fennell, a historian of IUPAC, “In 1977 IUPAP said it had lost interest as the existence of the two elements was doubtful anyway.”<sup>30</sup>

In a paper of 1976 a group of Western SHE specialists pointed out that lack of definite discovery criteria “has contributed significantly to the competing claims for the discovery for these [transuranic] elements.”<sup>31</sup> In discussing various ways of identifying new elements, some chemical and other physical, the authors emphasized proof of the atomic number as essential. The 1976 article was general in nature and did not apply the proposed discovery criteria to the ongoing priority controversies. But several years later three of the American co-authors published a detailed investigation of the discovery claims of elements 104 and 105 which was largely based on the 1976 criteria.<sup>32</sup>

The leading GSI physicist Peter Armbruster joined the debate in early 1985, expressing his wish of an international physics-chemistry commission taking care of the many controversies over names and discoveries. He proposed that “a name should be accepted only if the experiment claiming the discovery is reproducible.” Moreover, “An isotope is defined by its mass and atomic number, its fingerprints are its decay modes and its half-life.”<sup>33</sup> Armbruster’s paper most likely inspired IUPAP’s president, the Canadian-American nuclear physicist Allan Bromley, to suggest a working group of physicists to investigate priority questions related to the transfermium elements ( $Z > 100$ ). The result was the Transfermium Working Group (TWG) established jointly by IUPAP and IUPAC in 1985 and consisting of two scientists nominated by IUPAC and seven by IUPAP. To secure neutrality, none of the members were from USA, USSR or West Germany, the three nations with SHE facilities. The responsibility of the group, headed by the distinguished Oxford nuclear physicist Denys Wilkinson, was to formulate criteria for when

an element was discovered and to evaluate discovery claims accordingly.<sup>34</sup>

In a report published in *Pure and Applied Chemistry* in 1991 the TWG investigated systematically and thoughtfully criteria for recognizing the existence of a new chemical element. Of interest in the present context is the summary definition formulated by Wilkinson and his fellow TWG members: “Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide with an atomic number  $Z$  not identified before, existing for at least  $10^{-14}$  s.”<sup>35</sup> With regard to the requirement of a minimum lifetime of the nuclide it was introduced to make the formula more chemical and in accord with the standard view of the term element. “It is not self-evident,” the authors wrote, “that ‘element’ makes sense if no outer electrons, bearers of the chemical properties, are present.” It takes about  $10^{-14}$  second for a nucleus to acquire its electron system and thus to become an atom with certain chemical properties.

The same requirement was mentioned in the earlier mentioned report of 1976. “We suggest,” the authors wrote, “that composite nuclear systems that live less than about  $10^{-14}$  second ... shall not be considered a new element.”<sup>36</sup> So-called quasi-atoms of very high  $Z$  are formed transiently in heavy-ion collisions, but they exist only for about  $10^{-20}$  second. Consequently they do not qualify as nuclides of new elements. However, there seems to be no consensus among nuclear physicists of when a nucleus exists. Some take the definition of an atomic nucleus to be limited by the time scale  $10^{-12}$  second, and according to others “If a nucleus lives long compared to  $10^{-22}$  s it should be considered a nucleus.”<sup>37</sup>

The definition of an element did not change as the atomic number  $Z$  was still considered the defining property, as it had been since the early 1920s. On the other hand, the TWG report of 1991 pointed out that “The exact value of  $Z$  need not be determined, only that it is different from all  $Z$ -values observed before, beyond reasonable doubt.” That determination of the atomic number was still important is shown by the competing claims for having found element 113. When an IUPAC-IUPAP joint working party decided to attribute the discovery to the RIKEN team and not to the Dubna team, it was primarily because the first team provided solid evidence for the atomic number. The Dubna measurements, on the other hand, “were not able to within reasonable doubt determine  $Z$ .”<sup>38</sup>

The TWG was disbanded in 1991 but later on followed by other ad hoc inter-union groups of experts, generally referred to joint working parties or groups. For example, a five-member joint working party was

established in 2011 to examine claims of having discovered elements with  $Z > 112$  and another working party reported in 2016 on element 118. The discovery definition of TWG mentioned above was adopted by all the later working parties and can thus be ascribed an authoritative status.

## 5. DISCOVERED OR CREATED?

The various working groups established by IUPAC and IUPAP were concerned with the *discoveries* of new elements, a term used consistently in their reports. The press release issued by IUPAC on 30 December 2015 announced “the verification of the discoveries of four new elements” (namely  $Z = 113, 115, 117$ , and  $118$ ).<sup>39</sup> But although SHE scientists agree that their synthetic elements have been discovered, clearly this is in a different sense than the one we associate with the discoveries of, for example, gallium, argon and hafnium. Whereas the latter elements were found in nature, SHEs and artificial elements generally were *created* or *invented*, in largely the same way that a statue is created or a technological device invented. They belong to what the ancient Greeks called *techne* (human-made objects or imitation of nature) and not to *physis* (nature). To Aristotle and his contemporaries, *techne* denoted primarily a kind of craft or skill that could bring forth an artefact from the material nature.

Interestingly, Seaborg insisted that the transuranic elements he and others had found were created rather than discovered. “After all,” he said, “you can’t discover something that doesn’t exist in nature any more than Michelangelo discovered his David inside a block of marble.”<sup>40</sup> And yet Michelangelo did not think of his famous sculpture as just imposing form onto a lifeless block of marble, but rather as releasing a form that was imprisoned in the block. He reputedly said that he just cut away everything that wasn’t David.<sup>41</sup> By contrast, it makes no sense to say that a transuranic element is imprisoned in the nuclear reactants out of which it eventually emerges.

The creation of synthetic and yet in a sense natural objects did not start with the work of Segré and Perrier in 1937, for at that time there already was a long tradition in organic chemistry of synthesizing chemical compounds. The first such compound without a counterpart in nature may have been William Perkin’s famous discovery (or manufacture) of the aniline dye mauveine in 1856. The discovery initiated the synthetic revolution in chemistry, a revolution which has resulted in millions of man-made molecular compounds. In a sense the synthesis of transuranium elements is a continuation of the

tradition in synthetic organic chemistry, only at a more fundamental level.

When Mendeleev and his followers predicted from the periodic table that certain missing elements actually existed, they implicitly relied on a version of the so-called principle of plenitude.<sup>42</sup> According to this metaphysical principle as expounded by Leibniz and others, what can possibly exist does exist. Nature abhors unactualized possibilities. Or, in its modern version, if a hypothetical object is not ruled out by laws of nature it (most likely) will exist and thus be a real object. According to Leonard Susskind, a physicist and cosmologist, there are planets made of pure gold, for “they are possible objects consistent with the Laws of Physics.”<sup>43</sup> In this line of reasoning it is presupposed that existence refers to nature, but the situation with respect to SHEs is different as these elements are possible and yet not realized in nature. The potential existence is turned into actual existence not by finding a SHE in nature, as ordinary elements like gallium and germanium were found, but by creating it in the laboratory. The classical plenitude principle, expressing a belief in nature’s richness and continuity, does not seem applicable to the artificial world created by chemists and physicists.<sup>44</sup>

Whereas plutonium may be said to be a technological product, not only because it is man-made but also in so far that technologies are always purposeful and oriented towards social practices, this is not the case with most of the SHEs. They have been produced in minute amounts only and serve no social or economic purposes. The business of SHE research is fundamental science with no aim of contributing to technological and economic progress. It is science for the sake of science.

In a recent interview Yuri Oganessian justified his research field by saying that “it is about tackling fundamental questions in atomic physics.” Foremost among the questions is the prediction of an island of stability. According to Oganessian: “Theorists predict that there should be some superheavy atoms, with certain combinations of protons and neutrons, that are extremely stable ... but we are still far from the top of the island where atoms may have lifetimes of perhaps millions of years. We will need new machines to reach it.”<sup>45</sup> Other leading SHE scientists have expressed a similar *l’art pour l’art* attitude. The GSI veteran Sigurd Hofmann refers to the “sense of the excitement which has motivated workers in this field” and suggests that the motivation for study SHEs is “because we are curious.”<sup>46</sup>

But of course one may always fall back on the mantra, as two SHE nuclear chemists did in 1972, that “practical and useful applications would be forthcoming eventually, as is always the case with basic research.”<sup>47</sup> They



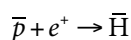
were referring to the possibility that long-lived SHEs might be discovered in nature. Should this be the case, unlikely as it is, these hypothetical elements would have been discovered in the traditional sense (or perhaps in the sense that technetium was discovered). But the short-lived isotopes below the island of stability would still belong to created and not discovered elements.

## 6. ONTOLOGICAL STATUS OF THE HEAVIEST ELEMENTS

As mentioned, SHE isotopes have short life-times and thus, in several cases they have been produced only to disappear again almost instantly. The elements have been produced and detected in nuclear processes and thus *did exist* at the time of the detection. But strictly speaking they *do not exist* presently any more than dinosaurs exist. The existence of SHEs is ephemeral or perhaps potential, which is quite different from the existence of ordinary elements whether radioactive or not. Can we truly say that the element oganesson *exists* when there is not, in all likelihood, a single atom of it in the entire universe? Sure, more atoms or rather nuclei of element 118 could be produced by replicating or modifying the Dubna experiments, which makes the element different from the long-time experiment of living nature known as the dinosaurs. But within a fraction of a second the re-created oganesson atoms would disappear again.

One may object that particles with even shorter lifetimes are known from high energy physics without physicists doubting that they really exist. For example, the neutral pion  $\pi^0$  decays into two gamma quanta with a lifetime of about  $10^{-16}$  seconds. The particle was first detected in nuclear reactions in Berkeley in 1950, but contrary to the nuclides of the SHEs it was also found in nature, namely in cosmic rays. The neutral pion thus exists and is not exclusively a laboratory product.

The same is the case with the antiproton, another exotic particle first produced in accelerator experiments, in this case in 1955, and only subsequently detected in the cosmic rays. Incidentally, in 1959 Owen Chamberlin and Emilio Segré – the co-discoverer of the elements technetium and astatine – were awarded the physics Nobel Prize for the antiproton experiment. The antiproton can be brought to combine with a positron and thus form anti-hydrogen according to



This exotic atomic system has been produced in the laboratory and studied experimentally.<sup>48</sup> Anti-hydrogen

atoms can under laboratory conditions survive for as long as 15 minutes. In 2011 an international collaboration of physicists reported observation of 18 events of artificially produced anti-helium  ${}^4\bar{\text{He}}$  consisting of two antiprotons and two antineutrons.<sup>49</sup> No anti-helium atom has been detected so far. Anti-hydrogen has in common with SHEs that it is element-like and only exists when manufactured. But contrary to the SHEs, there is no place for anti-hydrogen or other anti-elements in the periodic system.

There is also no place in the periodic system for other exotic atoms where the constituent protons and electrons are replaced by elementary particles such as positrons and muons. Positronium, a bound system of an electron and a positron, was discovered experimentally in 1951 but had been hypothesized almost twenty years earlier.<sup>50</sup> Sometimes described as a very light isotope of ordinary hydrogen or protium, the short-lived positronium has been extensively researched and its chemistry studied for more than half a century.<sup>51</sup> The positron can be replaced by a positively charged muon ( $\mu^+$ ) in which case one obtains muonium with an atomic mass  $A \approx 0.11$  between positronium and protium. First detected in 1960, muonium has a half-life of about  $2 \times 10^{-6}$  second.

If only a historical curiosity, ideas of exotic chemical “elements” had much earlier been entertained by a few chemists suggesting that the electron was such an element. This was what Janne Rydberg, the Swedish physicist and chemist, proposed in 1906, assigning the symbol E for the electron and placing it in the same group as oxygen.<sup>52</sup> Two years later, the Nobel laureate William Ramsay independently made a similar proposal, again using the symbol E.<sup>53</sup> But nothing came out of these speculations and when the atomic number was introduced in 1913, they were relegated to the graveyard of forgotten chemical ideas.

In 1970 the distinguished Russian nuclear chemist Vitalii Goldanski wrote a paper on SHEs and exotic atoms in which he suggested that Mendeleev’s table remained unaffected by the discovery of the latter kind of atoms. He wrote as follows:

*The replacement of electrons with other negative particles (for example,  $\mu^-$  or  $\pi^-$  mesons) does not involve a change in the nuclear charge, which determines the position of an element in the periodic system. As to the replacement of a proton with other positive particles, for example, a positron ( $e^+$ ) or  $\mu^+$  meson, such a replacement leads to the formation of atoms which in the chemical sense can be considered as isotopes of hydrogen. ... On the basis of the value of the positive charge [positronium and hydrogen] occupy one and the same place in the periodic table.<sup>54</sup>*

Goldanski's view is remarkable but also problematic, to say the least. Two widely different elements in the same box of the periodic table? Although muonium does not count as an ordinary chemical element it does have chemical properties and has even been assigned a chemical symbol (Mu). The analogy between muonic atoms and SHEs is underlined by the fact that the nomenclature of the first kind of atoms and their chemical compounds has been considered by IUPAC.<sup>55</sup>

A related question is whether short-lived transfermium elements really count as *elements* in the traditional meaning of the term. Elements consist of atoms and it is the atoms and their combinations which endow elements with chemical properties. An isolated atomic nucleus has no chemistry. This is what Wilkinson and his TWG stated in its 1991 report and more recently two nuclear chemists elaborated as follows: "The place an element occupies in the Periodic Table is not only defined by its atomic number, i.e. the number of protons in the nucleus, but also by its electronic configuration, which defines its chemical properties. Strictly speaking, a new element is assigned its proper place only after its chemical properties have been sufficiently investigated."<sup>56</sup> To phrase the point differently, although a chemical element is defined by its atomic number, not everything with an atomic number is an element.

The point is worth noticing as nuclear scientists commonly refer to an atomic nucleus or a nuclide as were it an element. For example, the 1991 TWG definition stated that a chemical element had been discovered when the existence of a *nuclide* had been identified. However, the term nuclide, coined in 1947, refers to a species of nucleus and thus emphasizes nuclear properties. By contrast, the corresponding and older term *isotope* denotes an atomic concept and emphasizes chemical properties. The difference between the two terms is more than just a semantic detail, but unfortunately the terms are often used indiscriminately.

Not only is the number of produced transfermium atoms extremely small, what are directly formed are nuclei and not atoms. Under normal circumstances a bare atomic nucleus will attract electrons and form an atom, but the circumstances of SHE experiments are not normal and the few atoms may only exist for such a small period of time that they cannot be examined experimentally. No atoms are known for the heaviest of the SHEs of which only atomic nuclei have been produced and studied. To this date, some 35 nuclei of livermorium ( $Z = 116$ ), all with half-lives less than 50 milliseconds, have been observed.<sup>57</sup>

Despite the elusive nature of SHEs nuclear scientists have succeeded in measuring some of their chemical

and physical properties. Ionization potentials have been measured up to lawrencium ( $Z = 103$ ) and even an element as heavy as flerovium ( $Z = 114$ ) has been the object of experimental study. Much is known also about other SHEs, but for some of them the knowledge is exclusively in the form of theoretical predictions, extrapolations and estimates.<sup>58</sup> For example, in the case of tennessine, element 117, its oxidation states have been predicted to be +1, +3, and +5; the electron structure and radius of the atom have been calculated and so have the boiling point and density of the element as well as of hypothetical compounds such as TsH and TsF<sub>3</sub>. But there are no empirical data and none are expected to come in the foreseeable future. Of course, the situation is different for the less heavy transuranic elements and especially for plutonium. Even some of the transactinides such as rutherfordium and dubnium have a real chemistry.<sup>59</sup>

Consider again the heaviest of the elements, oganesson, which is presently known only as one nuclide with an extremely small lifetime. To repeat, very few of the nuclei have been produced and none of them exist any longer. Oganesson has received official recognition from IUPAC and entered the periodic table alongside other and less exotic elements. And yet one may sensibly ask if oganesson is really a chemical element in the ordinary sense of the term. Perhaps its proper status is better characterized as a potential element, somewhat along the line recently suggested by Amihud Gilead, an Israeli philosopher of science.<sup>60</sup>

I am not arguing for an anti-realist position with regard to the SHEs at the end of the periodic table. Nuclides of these elements undoubtedly exist, or rather they existed at the time of their detection, but it is questionable if they exist or existed as proper chemical elements.

## 7. CONCLUSION

The study of the present state and historical development of SHEs is not only of interest to the historian of modern chemistry and physics but also raises questions of a more philosophical nature. Besides, in so far that much of the modern development of modern SHE research has taken place within the framework of a few competing nuclear laboratories and been evaluated by working groups established by IUPAC and IUPAP, it is also of interest from the perspective of sociology of science.

As pointed out in this paper, SHEs are not discovered in the normal sense of the term but are man-made objects the existence of which is entirely due to artificial nuclear reactions. The short-lived nuclides of SHEs

are ephemeral visitors to our universe, which calls into question the meaning of their existence. Although they have been officially recognized as chemical elements and designated places in the periodic table, it is far from evident that they can be properly characterized as elements. The old question of what constitutes a chemical element appears in a new light when seen through the lens of SHE research.

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